SPAR—A Soil-Plant-Atmosphere Research System

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ABSTRACT

COMPREHENSIVE studies of plant dynamics require simultaneous measurements of plant roots and tops in a controlled environment. The objectives of this research were to design, construct, and test a computer-controlled environmental system for studying whole-plant responses. Three independently controlled and monitored sunlit chambers, the Soil-Plant-Atmosphere Research (SPAR) system, were constructed at the USDA-SEA, Coastal Plains Soil and Water Conservation Research Center, Florence, SC. Each SPAR unit is a base steel soil bin, (2 x 0.5 x 1 m) on top of which is an acrylic plastic aerial chamber (1.5 m high), secured and sealed to the base. The temperatures of the aerial chamber and the soil bin can be controlled independently by air-conditioners and heaters. Micrometereological, soil, and plant variables are measured automatically with a micro-processor-based digital data acquisition system. In each chamber, CO_2 can be measured each minute to determine the amount of CO_2 absorbed by the plant, which must be replaced to maintain a constant CO_2 level. Apparent net photosynthesis is calculated from CO_2 measurements and corrected for chamber leakage.

The SPAR system was evaluated using cotton to determine the potential amount of root dry matter accumulation and proliferation in the soil under constant soil matric potential and non-limiting photosynthate supply. Initial results indicated that the SPAR system provides a precisely controlled soil and aerial environment to accurately and rapidly measure automatically some plant stresses and growth rates. Dependence of these rates on incoming energy indicates the need to rapidly and continuously measure soil-plant-atmosphere processes, because integration of these measurements for long periods tends to mask these responses.

INTRODUCTION

Recent plant-growth dynamic simulation models, developed by Baker (1965) and Curry (1971), have emphasized aerial plant processes. Since plant growth is highly dependent upon soil-water-root interactive processes, these processes must be understood and treated in dynamic plant-growth simulators. The temporal and spatial root distribution in relation to the distribution of soil water and nutrients must be known to determine water and nutrient uptake by plant roots. To calculate physiological stress, the affinity for metabolites in each of the plant organs must be known. To maintain the dynamic spatial root distribution, root growth simulation must be based on above-ground plant processes, root physiology and morphology, and soil properties. Gas exchange measurements are needed to determine photosynthesis, respiration, and transpiration as affected by the partial pressure of CO_2, solar radiation, temperature soil matric potential, and vapor pressure dificit.

Environmental chambers of various sizes and capacities have been designed and constructed previously to make these measurements: Moss (1963), Koller and Samish (1974), Jarvis and Slatyer (1966), and Hoffman et al. (1969). The advent of microprocessor and calculator-based data acquisition systems now permits simultaneous rapid control and monitoring of environmental variables as well as water regime and photosynthesis (McKinion et al., 1977). Soil-Plant Atmosphere Research (SPAR) systems, described in this paper will allow scientists to precisely and rapidly monitor the processes of plant growth, morphogenesis, photosynthesis, and transpiration, and to monitor and control the environment around both the aerial part of the plant and its root zone.

This paper describes the design and construction of the SPAR systems. Measurement and control methods of the system's parameters and variables tested are outlined in the procedures. Initial results of a performance test to determine the potential amount of cotton root dry matter accumulated under constant soil matric potential and at 600 mg/L atmospheric CO_2 level are presented.

DESIGN, CONSTRUCTION, MEASUREMENTS AND CONTROLS

Three independently controlled and monitored sunlit SPAR units are now in operation at the USDA-SEA Coastal Plains Soil and Water Conservation Research Center in Florence, SC. Each unit, shown schematically in Fig. 1a and photographically in Fig. 1b, consists of a base steel soil bin (2 m long x 0.5 m wide x 1 m high), covered with an acrylic aerial chamber (1.5 m high), that is secured and sealed to the top of the steel base.

Each SPAR unit was designed to contain two or more rows of plants, 0.5 m long, perpendicular to its long dimension, and oriented in a north-south direction.

Article was submitted for publication in August 1977; reviewed and approved for publication by the Soil and Water Division of ASAE in November 1977.

Contribution from USDA-SEA, Southern Region, and Department of Agricultural Engineering, Clemson University (Technical Contribution Number 1440).

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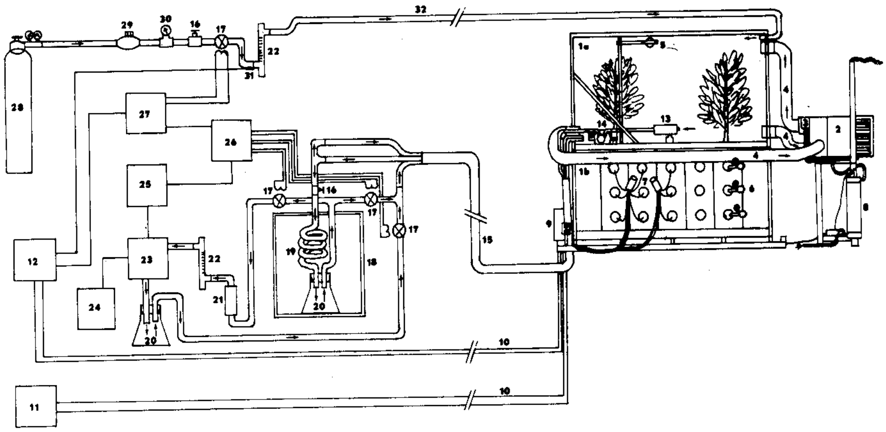
Acknowledgements: The authors express their gratitude to J. D. Vaught and M. W. Fisher for their assistance in the construction of the SPAR system, and to the support staffs from the Clemson Agricultural Engineering Dept. and the Coastal Plains Soil and Water Research Center for their participation in this project.

This article is reprinted from the TRANSACTIONS of the ASAE (Vol. 21, No. 5, pp. 924, 925, 926, 927, 928, 929, 930, 1978)
Published by the American Society of Agricultural Engineers, St. Joseph, Michigan



1. SPAR Unit
   a. Upper Plexiglas chamber
   b. Steel soil bin
2. Air conditioner
3. Heater
4. Air ducts (inlet and outlet)
5. Net radiometer
6. Tensiometers
7. Soil matric potential sensors
8. Transpiration measuring system
9. Electrical junction box (180 gold pin connectors)
10. Shielded wires for electrical connections
11. Calculator-based DDAS (measurement and control
12. Integrating DDAS (measurement only)
13. Psychrometer
14. Vacuum pump
15. Underground plastic tube for air samples
16. Manual gas flow control valve
17. Solenoid valves for automatic routing of air sample
18. Refrigerator for removing water from air sample
19. Water-condensing copper coil
20. Water trap
21. $Mg(CLO_4)_2$ drying tube for drying of air sample
22. Rotameter
23. CO_2 infrared analyzer (Beckman IR-15A)
24. CO_2-level strip chart recorder
25. Relay meter module for CO_2 level control
26. CO_2 sample scanner and solenoid valve controller
27. Solid state timer for timing of injected CO_2
28. Compressed CO_2 tank
29. Pressure regulator
20. Pressure gauge
31. CO_2 temperature measuring thermocouple
32. Dekoron plastic tube from lab to SPAR unit for injection of CO_2

FIG. 1a Schematic of SPAR system.

Each unit is provided with a pressure-regulated 19-mm water outlet, and equipped with a flowmeter (Rockwell, Model #SR) and a remotely controlled, electrical solenoid valve for automatic irrigaiton control. The soil bin is separated from the aerial chamber by plastic sheets, sealed around each plant and at the edges of the soil bin with duct tape to minimize gas exchange between the soil and areial chambers.

The ambient temperature in the aerial chamber is controlled within ±2.5 C of the control temperature by a 5.6-kW air-conditioner and a 5.8-kW electric heater. Air flow is shown schematically in Fig. 1a; the air-inlet ducts are mounted at the top and air exhaust ducts return the air from the lower portion of the aerial chamber (No. 4). Speed and mixing of the air is controlled by adjustable baffle plates mounted on the air-inlet ducts.

The temperature of the soil bins is thermostatically controlled by a brine flowing through copper tubing placed around each soil bin. Brine temperature is controlled by a heat pump, which heats or cools the brine in a 200-L tank. Soil and roots in each of the bins can be totally exposed on one side by removing an exterior lateral side panel (1 m high x 2 m wide). A grid of nine access ports (75 mm in diameter and 0.5 m apart) are located opposite this lateral side panel to provide quick access at 0.15-, 0.50-, and 0.80-m soil depths. These access ports, sealed with rubber stoppers (No. 14), may also be used to install sensors without removing the lateral side panel. Ceramic candles (0.45 m long and 5 mm in diameter, Selas flotronic*), connected 50 mm apart with flexible plastic tubing to a 12.7-mm diameter copper-tube manifold, were installed on a bed of fine sand about 25 mm from the bottom of the bin. These ceramic candles can be used for drainage, or to establish a given soil-matric potential or water table control by subirrigation. An electrical juction box, containing 180 individual gold pin connections, was installed outside each bin. Electrical conductors (18 AWG), shielded in groups of four, were buried underground in four neoprene-jacketed cables and used to connect instrumentation to computerized data acquisition systems, located in the laboratory, about 50 m from the SPAR units.

Aerial Chamber

The aerial chamber of each SPAR unit was constructed of 3.2-mm thick clear acrylic plastic sheets bolted to an aluminum angle frame and sealed with RTV*

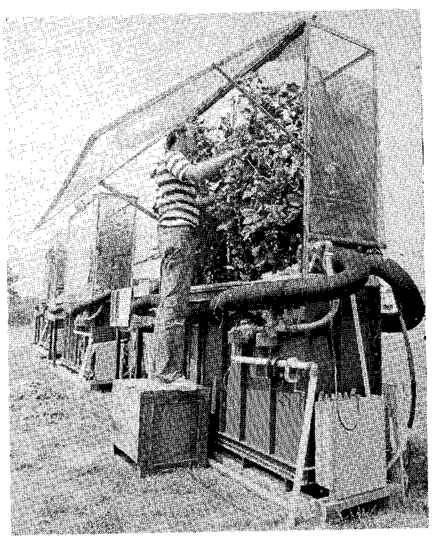


FIG. 1b The SPAR system.

*Trade names are used for identification purposes only and do not imply preference for this item by the USDA.

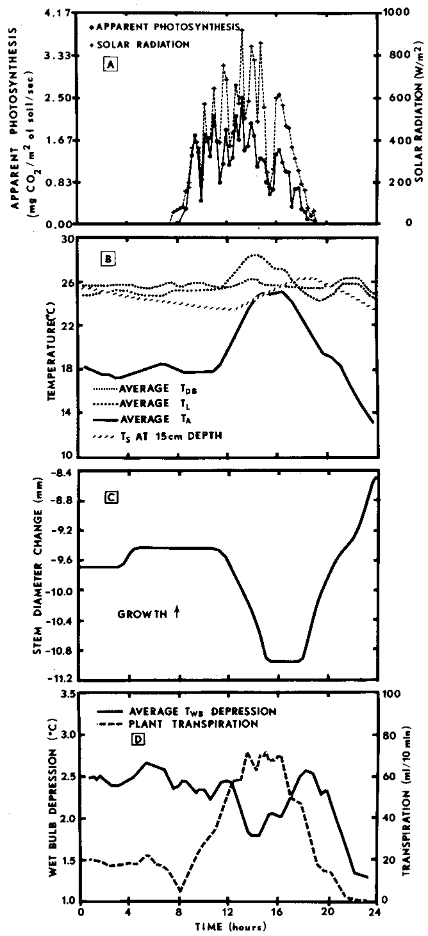


FIG. 2 Typical environmental and cotton plant measurements monitored in SPAR system maintained at 600 mg/L CO_2 content for day 269.

sealant. One of the lateral side panels (1.4 x 2 m) is hinged at the top of the aerial chamber (Fig. 1b) for access to the plants. A closed-cell molded rubber gasket is glued to this door and another to the frame to seal the door air-tight with latches. Each lateral acrylic plastic panel is partially shaded by an adjustable plastic screen which is raised daily to the height of the plant to simulate within-row shading as the crop grows.

Sensors and Data Acquisition Systems

Two Digital Data Acquisition Systems monitor and control variables in the SPAR systems. Micrometerological variables, like solar radiation (R_I); net radiation (R_N); ambient, leaf and soil temperatures; CO_2 assimilation; and relative humidity are measured by an Altair 8800A microcomputer-based digital data acquisition system (MDDAS), described by McKinnon et al. (1977).

Instrument output voltages are fed through a low thermal relay multiplexer into a voltage-to-frequency converter (VFC) to convert the analog signal to digital form. Each signal is integrated at the rate of two samples per second. Averaged measurements are linearized, converted to the desired units, and printed and punched on paper tape by a Teletypewriter (ASR-33)* every 15 min.

Soil matric potential (Phene et al., 1971, 1973), plant transpiration, and water stress are measured with a Hewlett-Packard 9100B calculator-based digital data acquisition system (CDDAS). Soil matric potential is measured, recorded, and printed hourly on a Teletypewriter (ASR-33), and is used to determine irrigation requirements and initiate automatic irrigation through the CDDAS. Transpiration is measured by collecting all the condensate from the cooling coil in a 100-mm diameter column and measuring the water level in the column with a float linked to a precision potentiometer. A solenoid valve, installed at the bottom of the water column, is opened automatically by the CDDAS for emptying the water in the column when the volume exceeds 3 L. Plant-water-stress is measured continuously with stem diameter-measuring instruments (LVDT) and calibrating these measurements with leaf water potential several times during the growing season (Parsons et al., in preparation). These measurements are used to evaluate treatment effects between SPAR units.

Incoming solar radiation (R_I) is measured with a black and white pyranometer (Eppley, Model #8-48)* mounted outside the chamber on the U.S. Weather Bureau instrument shelter. The output voltage of the instrument is integrated for 15 min and recorded with a microprocessor-based MDDAS. Fig. 2a shows the R_I time course for a 24-h period on day 269 (Sept. 26, 1975). Net solar radiation (R_N) is measured in each chamber with a Fritschen-type net radiometer. The net radiometers are adjusted laterally or vertically above the crop to measure an average of soil and crop net radiation. The output voltage of the instrument is integrated for 15 min and recorded with the MDDAS, according to the procedure used for R_I.

The 15-min averaged and instantaneous dry bulb temperatures (TDB) and wet bulb temperatures (TWB) are measured, respectively, with a thermocouple installed at the intake of the air pump, providing the air sample for CO_2 analysis, and with a Brady array humidity sensor (Thunder Scientific, Albuquerque, NM)* located in the same air stream. The thermocouple is positioned in a copper pipe 15 mm in diameter and thermally shielded with a 50-mm thick polyurethane casing. Typical TDB and TWB data for a SPAR unit are shown in Figs. 2b and 2d, respectively.

The average leaf temperature (TL) is measured for each chamber with a thermocouple threaded around one of the top leaf petioles with the junction taped to the underside of the leaf lamina. Measurements are integrated for 15 min. Cotton leaf temperature on day 269 is shown in Fig. 2b. The midday difference between TL and TDB (TL>TDB) is positive because of the imposed low soil-water potential. With high soil-water potential, a high transpiration rate at the leaf surface caused dissipation of heat energy, resulting in a negative TL-TDB differential (Baker, 1966).

The average and instantaneous soil temperature (TS) is measured at three depths in each soil bin with thermocouples, instrumentation, and recording technique described above. Fig. 2b is a typical 15-min average TS for day 269 at the 15-cm soil depth.

CO_2 Measurement and Apparent Photosynthesis Calculation

Fig. 1 shows the complete schematic of the CO_2 monitoring and control system for each chamber. The air sample from each chamber is passed through a condensing coil to remove the water vapor from the air. Part

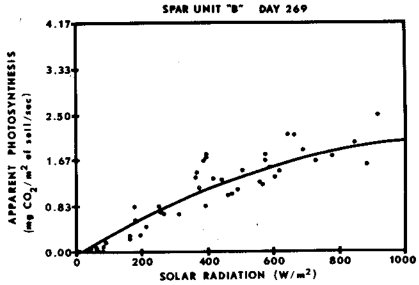


FIG. 3 Apparent photosynthesis as a function of solar radiation for cotton plants growing at 600 mg/L of CO_2 in SPAR unit B for day 269.

of the air sample is directed through a magnesium perchlorate drying column and then to the infrared CO_2 analyzer.

A three-channel scanner-controller was constructed to cycle the air sample from each chamber once per minute through the CO_2 analyzer. The flow rate through the CO_2 analyzer is regulated with a needle valve and monitored with a CO_2-calibrated 1.5-mm diameter rotameter. The voltage output from the CO_2 analyzer is connected to a relay meter with an adjustable set point. If the output of the CO_2 analyzer is low with respect to the set point, a timer is started, which opens the CO_2-line solenoid valve to feed CO_2 into the chamber for a predetermined time period. The flow rate of CO_2 is controlled by a needle valve and adjusted manually with a 1.6-mm diameter rotameter. The amount of time that the solenoid valve is opened is measured simultaneously by the MDDAS and a time-totalizing meter. The temperature of the CO_2 gas is measured in the rotameter, using a thermocouple, and the signal is integrated and recorded by the MDDAS. The CO_2 temperature measurement and the barometric pressure are measured continuously to provide pressure and temperature corrections for calculating the mass of CO_2 added to each chamber during the 15-min period.

Apparent net photosynthesis (N) is calculated from the plant absorption of CO_2 using the equation:

$$P_N = \frac{VCO_2}{At} \times \begin{matrix}\text{(Press.)}\\ \text{Corr.}\end{matrix} \times \begin{matrix}\text{(Temp.)}\\ \text{Corr.}\end{matrix} \times K$$

where P_N is CO_2 in gram per square meter of soil area per second, and VCO_2 is the volume of CO_2 added,

$$\text{Pressure correction} = \sqrt{\frac{\text{Standard barometric pressure}}{\text{Measured barometric pressure}}}$$

$$\text{Temperature correction} = \sqrt{\frac{\text{Measured absolute temperature}}{\text{Standard temperature}}}$$

$$K = \frac{44 \text{ g/g mol. wt } CO_2}{22.414 \text{ L/g mol. Wt } CO_2}$$

A = 1 m^2 (soil surface area)

t = integration time period (min)

In some experiments, the CO_2 level in the system is maintained above ambient; thus, a certain amount of CO_2 loss by leakage would be expected. A leakage test conducted for each unit without plants indicated a linear relationship between CO_2 loss and differential CO_2 pressure between the chamber and the free atmosphere outside. The ambient CO_2 concentration outside the system was measured continuously and used to provide a 15-min CO_2 concentration function, from which to calculate the differential CO_2 pressure. This coefficient obtained by linear regression for each chamber was used to correct for CO_2 leakage, based on the differential CO_2 pressure during the test. For unit B, operating at 600 mg/L CO_2 with an outside concentration of 310 mg/L CO_2, the leakage correction was 28.29 mg/L/min (0.0538 L/min). This CO_2 loss was subtracted from the CO_2 used before net photosynthesis was calculated.

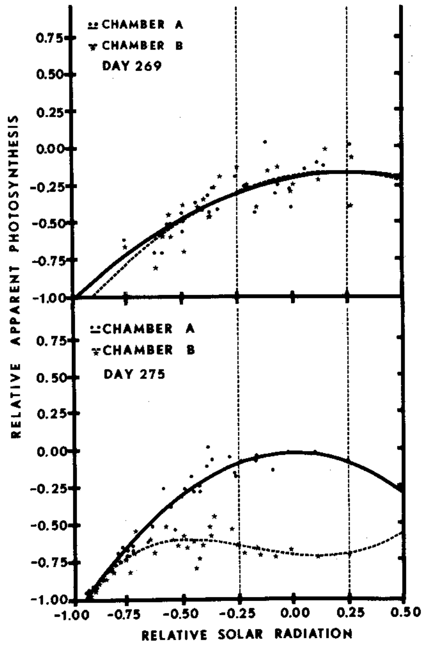


FIG. 4 Relative light response curves for cotton plants growing at 600 mg/L CO_2 in SPAR units A and B as affected by decreasing soil matric potential in SPAR "B". Irrigation was used in SPAR unit A to maintain the 0.15-m soil matric potential at -20 kPa.

Experiments for which this equipment was designed include the study of photosynthetic rates of plants as affected by rapid changes in external meteorological variables and soil water. Examples of the control achieved and the data required in this type of study are presented in Figs. 2 and 3. Apparent photosynthesis for cotton plants growing in SPAR unit B under a small water stress at 600 mg/L of CO_2 is shown as a function of time in Fig. 2a and as a function of solar radiation, measured outside of the SPAR system, (Fig. 3) for day 269. This light-response curve is essentially identical in shape to those obtained by similar techniques in actual field plantings of cotton (Baker, 1965).

The effect of soil water stress on apparent net photosynthesis is shown by comparing the relative light response curves for a SPAR system A, maintained at -20 kPa soil matric potential by daily irrigaitons, and SPAR system B, which was not irrigated between days 269 and 275. Relative P_N and R_I were calculated with respect to base day 229, when P_N and R_I had the largest values for the season:

$$\text{Relative } P_N = \frac{P_N \text{ (day 269 or 275)} - P_N \text{ (day 229)}}{P_N \text{ (day 229)}}$$

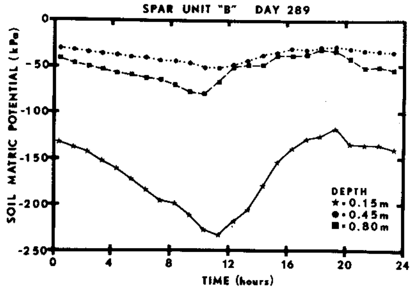


FIG. 5 Mean soil matric potential measurements at 0.15, 0.45 and 0.80 m depth for SPAR unit B on day 289.

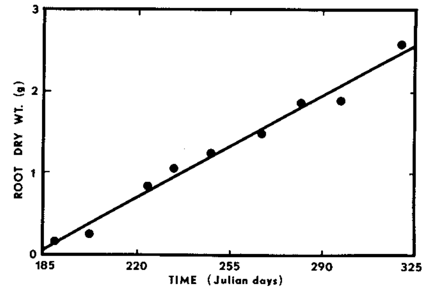


FIG. 6 Total dry weight of cotton roots obtained from 288 50-mm soil samples taken from SPAR unit A and representing a soil volume 71 x 10^{-4} m^3/sampling date.

$$\text{Relative } R_I = \frac{R_I \text{ (day 269 or 275)} - R_I \text{ (day 229)}}{R_I \text{ (day 229)}}$$

This method of comparing light response curves accounts for the decrease in solar radiation during the fall equinox. The region of interest in Fig. 4 is that which corresponds to nearly identical levels of solar radiation.

$$-0.25 < \text{Relative } R_I < +0.25.$$

Although this calculation method magnifies the P_N depression, it eliminates possible differences due to a changing R_I and/or differences in plant size between SPAR systems. Future experiments with the SPAR units will include a more detailed analysis of the effect of plant-water stress on photosynthetic rate of cotton.

Transpiration

Transpiration under constant relative humidity is measured in each chamber by collecting the water condensed by the air-conditioning coil in a column (100 mm in diameter) and recording the water level in the column every 10 min with the CDDAS. The bottom of the column has a solenoid valve, which is opened automatically by the CDDAS when the maximum water level is reached. Fig. 1a shows a schematic of the transpiration measurement system. The transpiration data for the cotton plants in chamber B on a typical day (269) is shown in Fig. 2d as a function of time and in relation to TWB. The total transpiration was 3906 mL (3.9 mm) for 24 h.

Soil Matric Potential Measurement

Soil matric potential was measured using the soil matric potential sensor, developed by Phene et al. (1971) (McCune-Neal Model #300B), and tensiometers (Soil Moisture Model #2725). Soil matric potential was measured each hour by the CDDAS at the positions (#7) shown in Fig. 1. Tensiometers are also read in each bin, twice daily, at 0830 and 1630 h, at the 0.15-, 0.50-, and 0.80-m depth below the soil surface. Typical hourly mean soil matric potential measurements at each depth are shown in Fig. 5 for SPAR unit B during the 1976 experiment.

Stem Diameter Measurements

Plant stem diameters are measured by linear displacement precision potentiometers and linear variable displacement transformers (LVDT) attached to the plant stem. The potentiometers are interfaced to the CDDAS through a Wheatstone bridge with a zero offset and calibrated to measure displacement directly by adjusting the bridge voltage. Fig. 2c shows a typical 24-h stress-growth cycle as a function of time for a cotton plant growing in SPAR unit B.

Irrigation System

The irrigation system, installed on the soil surface in each soil bin, consists of a 25-mm diameter PVC manifold into which 13 0.5-m long pieces of porous plastic tube (Viaflo, E. E. DuPont & Co.) have been connected. The irrigation system pressure is regulated at 20 kPa pressure and is set to deliver water automatically and uniformly at a rate of 650 mL/min/unit. Manifold pressure is set by a pressure regulator (Watts Model #N26), and the irrigation water applied daily is determined by a flow meter. Manual and solenoid valves are provided for either manual or automatic control of the irrigation system. In the automated mode, irrigation is controlled by an electronic feedback from the soil matric potential sensor (Phene et al., 1973). Soluble fertilizers and pesticides are injected through the irrigation system by a precision metering pump (Electro-Feeder, chemical metering pump, type G).

EVALUATION OF SPAR SYSTEM

Performance of the SPAR system was experimentally tested and the potential amount of cotton root dry matter accumulation and proliferation in a soil under constant soil matric potential with nonlimiting photosynthate supplies was determined. The soil bins were filled with air-dried Cecil sandy loam topsoil and vibrated and wetted for compaction. Dolomitic lime was applied at the rate of 5000 kg/ha, based on a soil test, and mixed uniformly in the upper 0.3 m of soil at planting. Fertilizers were banded 0.1 m from each row and 0.12 m below the the soil surface to provide the equivalent of 100 kg/ha N, 25 kg/ha P, 55 kg/ha K, 34 kg/ha Mg, and trace of B. Two rows of cotton (*Gossypium hirsutum L.*, Cv Stoneville 213 var.) 0.5 m long, spaced one m apart, were planted on May 27, 1975 (day 147) and thinned to five plants per row. To provide as much photosynthate as possible for root growth, all fruit (squares) was removed weekly. The fact that nonlimiting photosynthate supplies were achieved is demonstrated by the linear (as opposed to sigmoid) seasonal time courses of dry matter accumulation in roots (Fig. 6) and leaf area (Fig. 9). Detailed results of this root study are reported elsewhere (Lambert et al., 1975).

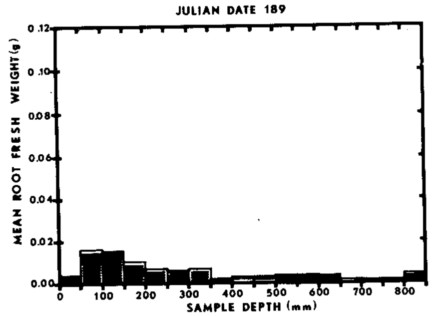


FIG. 7a One-dimensional root map for cotton grown at 600 mg/L CO_2 in SPAR unit A on day 189 [planting date: JD 147].

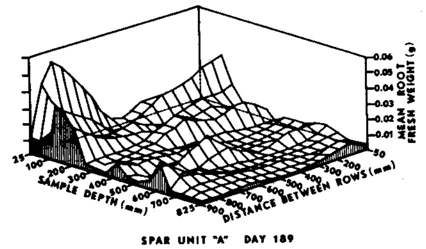


FIG. 7b Two-dimensional root map for cotton grown at 600 mg/L CO_2 in SPAR unit A on day 189 [planting date: JD 147].

Root Measurements

Determinaiton of spatial and temporal root distribution was obtained by periodically sampling the soil in SPAR unit A. A 25-mm diameter thin-wall stainless steel soil sampler was constructed to take 20 subsequent 50-mm long cores from the soil surface to the bottom of the bin. To prevent sampling in the same hole twice, a sampling grid template was constructed with the sample positions randomized for 18 sampling positions across the row for each of the nine sampling dates, with one position sampled at each sampling date. Fresh and dry root mass and root diameters were measured from these soil samples. Fig. 6 shows the total dry weight of cotton roots obtained for each sampling date plotted as a function of time. One-and two-dimensional fresh-root-weight diagrams are shown in Figs. 7a and b for SPAR unit A on day 189 and in Figs. 8a and b for day 321.

Plant Measurement

Leaf area index (LAI), number of leaves per plant, plant heights, and node counts were measured weekly in unit C. Results obtained are plotted as a function of time in Fig. 9. The nondestructive leaf area of each plant was estimated (± 5 percent) by visually matching leaves to a template containing leaves of known area. Plant heights were measured until the top of the plant reached the top of the chamber. Fig. 10 shows the cumulative number of cotton blooms removed as a function of time for each of the SPAR units.

SUMMARY AND CONCLUSIONS

The initial testing of the SPAR units indicated that this naturally sunlit system provides a precisely controlled soil and aerial environment for plant growth. Accurate and rapid measurement of transpiration and photosynthetic rates can be obtained automatically. Dependence of these rates on incoming energy indicates the necessity for rapid and continuous measurement of soil-plant-atmosphere processes, to understand plant response to the environment and to apply the results to validation of dynamic simulation models. Integration of these measurements for long periods tends to mask these responses. Because of the accessibility of the plants and soil system, plant and root measurements can be performed precisely and with minimum disturbance to the system. Careful experimental design and data collection will also provide data bases for development and validation of dynamic plant growth simulators.

Natural sunlight provides the SPAR system with the radiation intensity and variation and the spectral distribution which are difficult to obtain in artificially-lit growth chambers. Natural sunlight may also be supplemented by artificial lights during cloudy periods to provide a more constant radiation load to the system. On the other hand, programming the radiation regime, controlling environmental variables, and insulating the systems and instruments are more difficult with an outdoor system than with growth chambers installed in a phytotron-like environment.

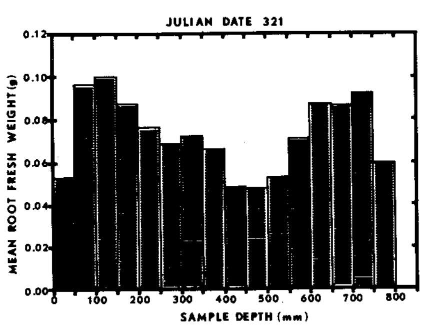


FIG. 8a One-dimensional root map for cotton grown at 600 mg/L CO_2 in SPAR unit A on day 321.

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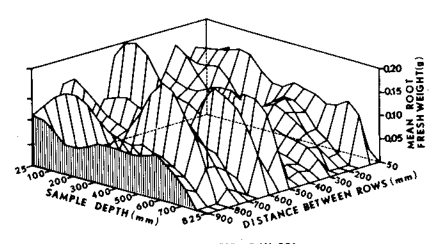

FIG. 8b Two-dimensional root map for cotton grown at 600 ml/L CO_2 in SPAR unit A on day 321.

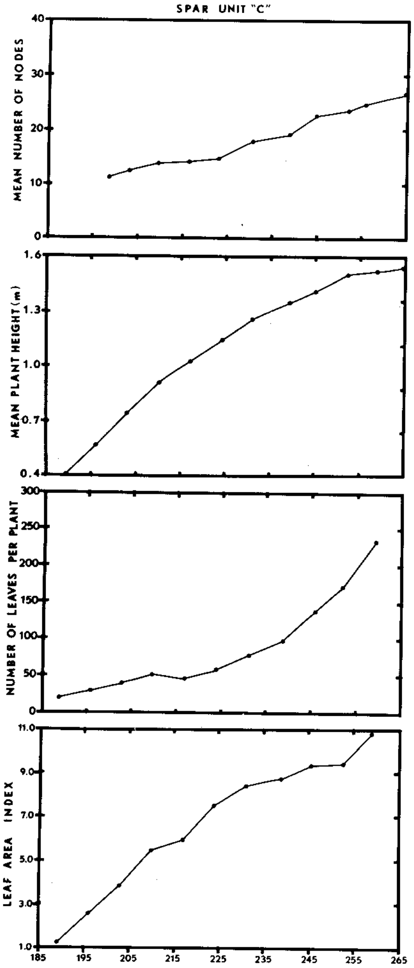

FIG. 9 Plant variable measurements for cotton growing in SPAR unit C at 600 mg/L CO_2 for 1975.

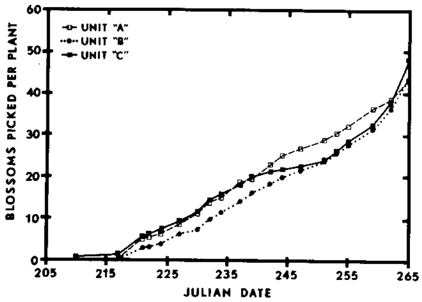

FIG. 10 Cumulative number of cotton blooms removed for SPAR units A, B, and C.

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